

Life cycle inventory analysis on Bio-DME and/or Bio-MeOH products through BLUE tower process

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Abstract

Background, aims, and scope In this study, we focused on the biomass di-methyl ether (Bio-DME) and the biomass methanol (Bio-MeOH) in BTL (Biomass to Liquid) fuels which might bring a solution on an energy storage and/or CO₂ emissions abatement. For these fuels, our object is to estimate CO₂ emissions and energy intensities (the specific energy consumption in each sub-process) for the biomass liquefaction system, which is expanded to material's transportation, energy conversion and fuel transportation in detail. **Materials and methods** In this paper, we estimated life cycle inventories (CO₂ emissions and energy intensities) on Bio-DME and Bio-MeOH using the bottom-up methodology. The system boundary consists of the pre-processing, the biomass liquefaction process and the fuel transportation. In order to evaluate the uncertainties in the pre-processing, the moisture content of biomass materials and the transportation distance to the plant were considered by the Monte Carlo simulation. Also, in the energy conversion process, our system is built up by gasification through the BLUE Tower (BT) process, with the liquefaction process. In

addition, in the fuel transportation, we assumed that the liquefied fuel (Bio-DME/Bio-MeOH) was delivered to the end-users at a distance of 209 km round trip.

Results First, the assumptions for estimation of CO₂ emissions and energy intensities in the pre-processing were as follows: The biomass materials are the waste products from Japanese Cedar. Also, the uncertainties of moisture content and transportation distance are assumed to be 20 to 50 wt.% and 5 to 50 km, respectively. In the case that the reaction temperature and the pressure in the liquefaction plant were 210–290°C and 2.0–5.0 MPa of DME/MeOH synthesis, the production rate of DME is 37,634 to 44,912 GJ/yr, and that of MeOH was 30,562 to 39,865 GJ/yr. These production rates are used as functional units of CO₂ emissions and energy intensities. Under these operational conditions, CO₂ emissions for the entire system are 42.3–64.6 g-CO₂/MJ-Fuel of Bio-DME, and 48.3–77.7 g-CO₂/MJ-Fuel of Bio-MeOH, respectively. Also, energy intensities are 1.22–1.65 MJ/MJ-Fuel of Bio-DME, and 1.42–2.03 MJ/MJ-Fuel of Bio-MeOH, respectively.

Discussion The effects on the operation conditions of temperature and pressure were as follows: In general, in the liquefaction synthesis, a good result (the liquefied fuel at a higher efficiency) is obtained as the pressure would be increased. Also, the temperature to encourage the reaction well is required to some extent. The specific CO₂ emissions would decrease as the temperature drops. Note that the minimum temperature of DME or MeOH synthesis is at least 210–220°C. Meanwhile, CO₂ emissions would decrease as the pressure increases. However, in the case of Bio-DME fuel, CO₂ emissions would be slightly worse. This implies that the production rate is not ideal, compared to the total energy consumption. In all conditions we analyzed, Bio-DME/MeOH production indicated that energy intensities were lower than 2.0 MJ/MJ-

The Blue Tower is a reformation gasification system which handles the disposal of multi-feedstock such as municipal solid waste.

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Fuel, and that there was a potential to mitigate CO₂ emissions.

Conclusion We focused on a small gasification-liquefaction plant from the perspective of biomass resources distribution. Although this circumstance might be unique to Japan, the plant scale for the biomass energy use would not be able to expand. Nowadays, the fuel of biomass to liquid (BTL) is exceedingly being counted on as a promising fuel, so as to reduce CO₂ emissions. However, when considering the collection area of biomass resources, the moisture content, the plant scale and the auxiliary power, it is implied that Bio-MeOH/DME does not always reduce CO₂ emissions on an LCA basis, compared to a conventional plant.

Recommendations and perspectives The LCA of the small scale biomass energy system we treated in our study is extremely significant to build a sustainable biomass energy system, since we presume that the utilization of biomass resources would compete with other strategies such as food production, etc. For future work, the feasibility studies on the wheel efficiency and/or the investigation of demand of DME/MeOH will be required from the perspectives of a diversity of energy sources, and/or alternative fuels use.

Keywords Bio-DME · Bio-MeOH · Biomass materials · BLUE Tower (BT) process · CO₂ emissions · Energy intensities · Monte Carlo simulation · Uncertainties on the moisture content · Uncertainties on the transportation

1 Background, aim, and scope

Since the Kyoto protocol has come into effect in 2005, the technology on CO₂ emissions mitigation has developed significantly. In particular, the biomass energy system, that is, the energy system using biomass materials such as wood, organic waste, sewage and similar material, is one of the promising energy systems to abate CO₂ emissions. As is well known, the biomass energy use by burning would be zero emissions due to it being “carbon neutral”. However, there are still several problems in the use stage. For instance, wooden materials are generally distributed over a more wide area. That is, for the reason of longer transportation distance, the total cost and CO₂ emissions would be increased. Also, although gasification technologies have attracted attention from all over the world, as one of the future technologies, their energy efficiencies are quite different, due to the energy conversion methodologies. Thus, under these circumstances, the energy production cost is likely to still be high, even if related subsidies, environmental regulations and/or policies are put in place to support them.

In the early stages, it was thought that the biomass energy system, through gas-engine cogeneration, would be

a mainstream. However, since there is a discrepancy between the demand and the supply, that is, since the produced energy cannot be stored, the energy of electricity and/or heat would be excessive. Consequently, in such a system, CO₂ emissions mitigations could not be realized, and the energy production cost would be expensive.

With this as its background, the Japanese government has tried to promote the biomass energy system as an effort to solve global warming. As an example, the Ministry of Economy, Trade and Industry (METI) predicts the biomass energy use of 39.1 PJ in the future energy demand and supply plan of 2010. Also, on the production cost of BTL fuel, the efforts to lower the cost 40 yen/L by 2015 has begun to be executed (METI 2007). The Ministry of Agriculture, Forestry and Fisheries (MAFF) also predicts biomass energy use of 110.5 to 210.1 PJ in the future energy demand and supply plan of 2010. Especially, MAFF has a project to produce BTL fuel of 5.0×10^8 L in the transportation sector (MAFF 2006).

On the other hand, transportation is a key energy-consumption sector, responsible for 31% of final energy demand in the EU. Also, it is a main contributor to the growth in energy demand, with its energy consumption increasing faster than total gross energy consumption. Thus, securing and diversifying the energy supply for road transportation in an environmentally-friendly way, is a prime objective for energy and environmental policies. By 2010, there is a project to introduce BTL fuel of approximately 0.38 GJ through gaseous synthesis processing (European Commission 2005).

In the entire system design, the estimations of CO₂ emissions and/or energy intensities due to LCA methodology are very important. Recently, in Japan, the Bio-ethanol (Bio-EtOH) is imported from Brazil, where the bio-liquid fuel (Bio-EtOH) is synthesized from sugar cane. In this case, the contributions to CO₂ emissions and/or energy intensities would be due to the sea transportation to Japan, the auxiliary power in the biomass energy plant, and the materials pickup by trucks, etc.

The main objective of BTL fuel use is to mitigate CO₂ emissions, compared with conventional fuel. Thus, when we estimate CO₂ emissions or energy intensities for the fuel production, we have to consider the energy consumption of fossil fuel origin in each process more concretely.

So far, there is the result of Peter et al. as the related studies on BTL fuel production (Peter and Brandberg 2001). In that study, although LCA on DME/MeOH production of biomass materials was executed, the more detailed information on energy conversion technology and the species of biomass materials were not necessarily explicit. That is, this means that the detailed technological conditions and/or the concrete assumptions should be required in such an analysis in order to clarify the effectiveness. That attributes the

effectiveness of CO₂ emissions mitigation in the proposed energy system. Also, in LCA on the biomass energy system, there are a few uncertainties on the estimation of CO₂ emissions. These uncertainties may include moisture content, and/or the transportation distance between the locations of waste materials and the plant. Thus, we are concerned with influences caused by uncertainties in the biomass energy system.

In this paper, the uncertainties of the transportation distance for biomass collection and of the materials condition (moisture contents) are referred by Monte Carlo methodology. For instance, the biomass resources exist thinly. That is, the resources are distributed in many locations and in wider areas. The biomass throughput, by which the system can be operated in the biomass energy plant, is required every year. Therefore, the plant location is dependent upon the conditions of biomass resources location, and of the transportation roads, and the requests from the local government and/or other groups where the plant will be constructed. Also, the moisture contents of the biomass materials are dependent upon seasonal conditions. Thus, the transportation distance might reach several tens of kilometers to operate the plant well. Regarding the reliability of the biomass energy conversion technology, there are some uncertainties, too.

Up until now, the focus has been on the use of biomass resources and biomass energy systems, such as the biomass gasification process, which have mainly been developed in Europe. Above all, we think that the BT process, which is developed by D.M.2 Projekt GmbH, is close to being realized as a commercial plant. The characteristics of the BT process are similar to the indirect gasification process with a pyrolyzer. This gasifier has three reactors for the preheating process, the reforming process and the pyrolysis process. The gasifier has the following characteristics; 1) pyrolysis reactions take place in the pyrolyzer, 2) pyrolysis gases are reformed by H₂O (steam), 3) heat required for their reactions is supplied by combustion of off-gas, Tar and Char. Additional heat through a chip boiler might be required in order to accelerate the reactions well. With regard to the gasification performance, the gaseous yield and concentration are dependent upon the kinds of materials, the operating temperature, and the inner pressure (Mayer et al. 2004; Schmid and Mühlen 1999). Thus, in order to evaluate the reliability of BTL fuel production, we fabricated an apparatus, which included the concept of the BT process (a pyrolyzer and a reformer), and we executed the basic chemical experiments using the wood sample of Japanese Cedar with the size of 2–3 mm. In the experiments, we measured the syngas components and estimated the equilibrium constants, adjusting the temperature condition and/or steam-carbon ratio (S/C). In this paper, we focused on the wood pallets from carriers, and/or the

wasted materials (chopped materials) from sawmills. In the BT plant, these materials chopped at the size of 20–30 mm are fed into the reactor. In the case of Japanese Cedar (waste wood) as biomass materials, H₂ of 54.4 vol.% and CO of 24.4 vol.% were generated at 950°C and Steam/Carbon=1.0 (Dowaki et al. 2007). The mole ratio of H₂/CO through the gasifier is likely to be >2.0. That is, the syngas would be suitable for the production of DME/MeOH due to an indirect method. Note that, on the portion of liquefaction synthesis, we computed the reaction rate due to the equilibrium theorem.

Using these data, we designed the plant specification of 10 t-dry/d scale, which is an average plant scale in the system. Especially, if we consider the amount of waste wood which would be distributed in a given, local area of Japan, the available plant-scale would be 30 t-dry/d at most, from the viewpoint of cost benefits.

Next, using the gasification specification data, we estimated the production rates of DME or MeOH through biomass materials origin. However, note that theoretical investigation was executed based on the equilibrium law on DME synthesis or MeOH synthesis in this paper, since we could find no experimental data of DME/MeOH synthesis considering the small plant and biomass materials in this study. According to the gaseous yields of H₂ and CO, the liquefaction method we focused on is suitable for the indirect one that is often used in DME and/or MeOH synthesis by natural gas.

Finally, we analyzed the production rate and the auxiliary power, varying the operational conditions. We estimated CO₂ emissions and energy intensities in the whole system. The results were compared with the production of these fuels from natural gas (NG). Significant results will contribute to the biomass liquefaction plants, which will be built in the near future.

2 Concept of the biomass life cycle assessment

So far, the biomass Life Cycle Assessment (LCA) analyses, in which the pre-processing process of chipping, transportation and drying of biomass materials are included, and in which the energy conversion process of a production energy of electricity and/or heat, through an integrated gasification combined cycle (IGCC) power system or a co-generation system (CGS) is included, were analyzed (Dowaki et al. 2002; Dowaki et al. 2003). In this paper, we focused on DME and/or MeOH fuels. The design of the BTL plant using the chemical experimental data would be extremely significant in the biomass LCA.

At the beginning, in this section, we defined the system boundary of the biomass LCA.

A target is to estimate a life cycle inventory (CO₂ emissions and/or energy intensities) of the entire system with a biomass gasification and a liquefaction. That is, we refer to the environmentally friendly system, such as the biomass energy system, considering CO₂ emissions and/or energy intensities from the entire system based on LCA methodology. Also, there is a trade-off relationship between the production rate and the operational conditions. If the reaction pressure goes up, the production rate is increased; however, since the auxiliary power is increased, CO₂ emissions and energy intensities become worse. We investigated the effects of the operational conditions, too.

2.1 System boundaries

Following ISO 14041 guidelines, we define the system boundary in the biomass energy system.

The system boundary includes the entire life cycle of the BTL fuel product (DME/MeOH), including the pre-processing process, the energy conversion process and the fuel transportation process (Fig. 1). In the pre-processing process, there are sub-processes of chipping, transportation by trucks, and drying. In the energy conversion process, there are sub-processes of the gasification through the BT plant with a liquefaction process. In the fuel transportation process, it is assumed that liquefied fuel is delivered to the end-user by trucks.

2.2 Functional unit

The target product is Bio-fuel: DME or MeOH. Thus, in this paper, the functional unit is assumed to be the unit per a produced energy. The lower heating values of DME and MeOH are 28.8 MJ/kg and 19.7 MJ/kg, respectively. The

conventional electricity is 9.0 MJ/kWh as a primary energy (ECCJ 2004).

3 Pre-processing process

In the pre-processing process, there are sub-processes of chipping, transportation, and drying of biomass materials. In particular, within the sub-processes of transportation and drying, we have to consider uncertainties. To date, there are few studies considering these uncertainties. CO₂ emissions and energy intensities in the biomass LCA would be affected by the moisture content of biomass materials, and the transportation distance from the cultivation site, or the site of accumulating waste materials, to the energy plant. Table 1 shows heating values, and that of CO₂ emissions, for each fuel with biomass materials, respectively. Also, CO₂ emissions and energy intensities were estimated using the Monte Carlo simulation in order to consider these uncertainties.

3.1 Sub-processes of chipping, transportation and drying

The energy consumption of chipping, transportation and drying is as follows:

- Chipping* The energy consumption of the chipping process is due to electricity and diesel. The specific units of energy consumption are 13.6 kWh/material-t (122.4 MJ/material-t) and 1.23 L-diesel/material-t (43.7 MJ/material-t), respectively (Hashimoto et al. 2000).
- Transportation* The chopped biomass materials are delivered to the plant by 10 ton diesel trucks. CO₂ emissions and/or energy intensities on a given transportation run would be affected by the weight of biomass materials. That is, the weight of which the

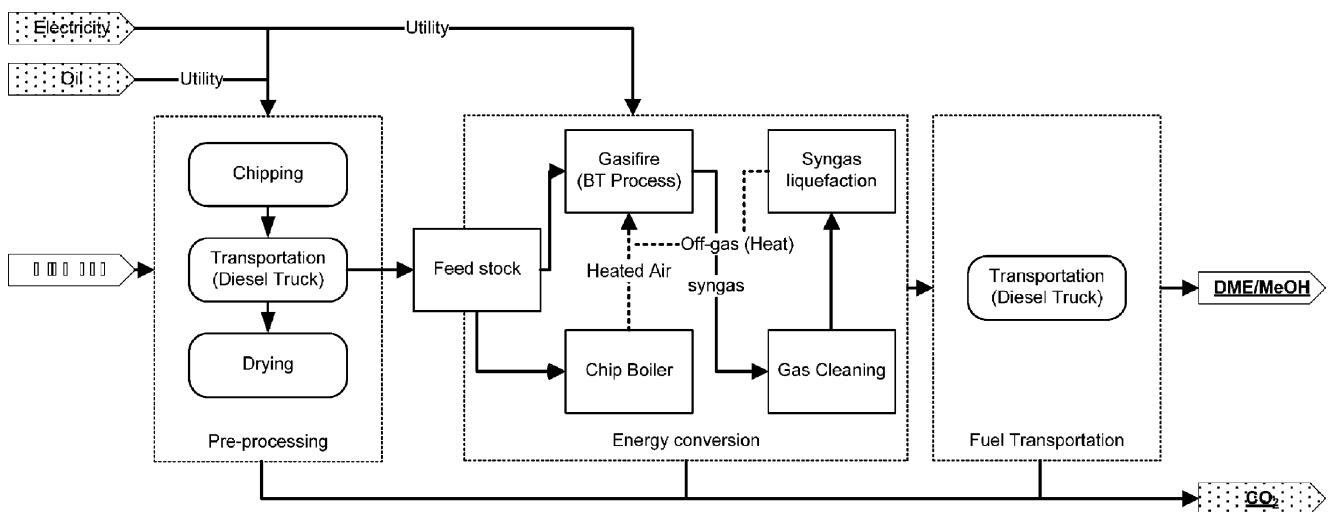


Fig. 1 System boundary of DME/MeOH production

Table 1 Data of fuel energy and CO₂ emissions

Fuel	Energy(LHV)	CO ₂	Note
Biomass	13.65 MJ/kg	0.0 g-CO ₂ /MJ-Fuel	at 20 wt.% (moisture content), Japanese Cedar
Diesel	35.50 MJ/l	79.82 g-CO ₂ /MJ-Fuel	Chipping, Transportation
Electricity	9.0 MJ/kWh	123.1 g-CO ₂ /MJ-Fuel	Auxiliary power of the plant (Primary Energy)

materials can be carried is restricted to bulk density. We measured the bulk density ($=0.14 \text{ t/m}^3$) in the atmosphere. The bulk density is dependent upon the moisture content. Thus, assuming that the bulk density is at a moisture content of 15 wt.% (ρ_{15}), the bulk density ρ_{MC} at any moisture content (MC wt.%) is:

$$\rho_{MC} = \frac{0.85}{1 - MC} \rho_{15} \quad (1)$$

Next, the loading platform of 10t-trucks is to be approximately 24.7 m^3 (Suri-Keikaku 2005). Consequently, even a truck with 10 ton's volume cannot always carry that in full weight. Here, CO₂ emissions and/or energy intensities are assumed to be due to the fuel consumption of truck, which is indicated as a function of the loading rate of weight. That is, using the loading rate of λ , the fuel consumption rate of a 10t-truck $f_{FC}(\lambda)$ is:

$$f_{FC}(\lambda) = a\lambda + b \quad (2)$$

where, $a(=714 \text{ g-CO}_2/\text{km})$ and $b(=508 \text{ g-CO}_2/\text{km})$ are constants on the fuel consumption of the truck (Dowaki et al. 2008).

The definition of the loading rate of λ is as follows: Assuming that the plant scale is 10 dry-t/d, and that the annual operating time is 300 days, the annual material balance on the feed materials is 3,000 t-dry/yr. Since the throughput per year at MC wt.% is $3,000/(1 - MC)$, the total number of transportation by 10 t trucks at MC wt.% (N_{mat}) is:

$$N_{\text{mat}} = \left\lceil \frac{3,000/(1 - MC)}{24.7\rho_{MC}} \right\rceil + 1 \quad (3)$$

Where, $[\alpha]$ is represented as the maximum integer, so as not to exceed α . Thus, the average loading rate of a 10 t-truck (λ_{ave}) is:

$$\lambda_{\text{ave}} = \frac{3,000/(1 - MC)}{10N_{\text{mat}}} \quad (4)$$

Providing the average loading rate, and multiplying $f_{FC}(\lambda)$ by the transportation distance and the specific CO₂

emissions or the energy consumption of diesel, we can estimate CO₂ emissions or fuel consumption in the transportation sub-process. In this paper, the transportation distance is the range between 5 (Dist_{min}) and 50 km (Dist_{max}), because the wooden materials in Japan are distributed widely. That is, it is assumed that the feed materials are collected within a radius of 50 km.

- (c) *Drying* Next, on the sub-process of drying, the energy consumption was estimated under the condition that the moisture content of feed materials would decrease to 20 wt.%. Here, assuming that the initial moisture contents are from 20 (MC_{min}) to 50 wt.% (MC_{max}), the raw materials are dried by a boiler. Also, the auxiliary power of a pump in a boiler is included in the energy consumption of the sub-process. The operational specification of a wood-chip dryer (boiler) is the energy efficiency of 80%, and the auxiliary power of a pump of 0.195 kWh/t-water (1.75 MJ/t-water).
- (d) *Monte Carlo simulation on the uncertainties* As the above, in this paper, we estimated CO₂ emissions and/or energy intensities, considering the uncertainties of the transportation distance and the moisture content. In this paper, the following two uncertainties of the distance and the moisture content were considered by the Monte Carlo simulation.

That is, the uncertainties on the transportation distance (Dist km) and the moisture content (MC wt.%) are represented by uniform random numbers Rnd_i between 0 and 1 in Eqs. (5) and (6). Note that Rnd_1 and Rnd_2 are independent and identically distributed.

$$\text{Dist} = \text{Dist}_{\text{min}} + \text{Rnd}_2(\text{Dist}_{\text{max}} - \text{Dist}_{\text{min}}) \quad (5)$$

$$\text{MC} = \text{MC}_{\text{min}} + \text{Rnd}_1(\text{MC}_{\text{max}} - \text{MC}_{\text{min}}) \quad (6)$$

An iteration count in the simulation was executed up to 10,000. The range within a 95% significant level was adopted as the uncertain data on the distance and the moisture content, in order to estimate CO₂ emissions and/or energy intensities. In this case, the gross distributions on CO₂ emissions and/or energy intensities would be normal distributions.

Table 2 Gas components for liquefaction process

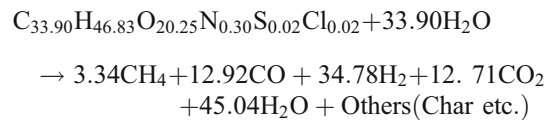
Component		Gaseous Yields
Material Gas	N ₂	20.2 vol.% ¹⁾
	CH ₄	0.20 vol.% ¹⁾
	CO	21.6 vol.% ¹⁾
	H ₂	42.3 vol.% ¹⁾
	CO ₂	14.7 vol.% ¹⁾
	C ₂ H ₄	ND
	C ₂ H ₆	ND
	HC 1	1.9 ppmV ²⁾
	H ₂ S	2.7 ppmV ²⁾
	NH ₃	0.1 ppmV ²⁾

1) vol.%;volume percentage; 2) ppmV: ppm volume

3.2 Sub-processes of an energy conversion through the BT plant with a liquefaction process

The BT process, which was developed by D.M.2 Projekt GmbH, is an entirely new technology for recycling natural resources and/or biomass materials. Through a reaction process based on hot steam, the biomass is converted to a syngas with a high concentration of H₂. The BT process has the following characteristics: 1) pyrolysis reactions take place in a pyrolyzer, 2) pyrolysis gases are reformed by H₂O (steam) and, 3) heat required for their reactions is supplied by combustion of off-gas, Tar and Char.

(a) *Gas components through gasification experiments:* With regard to the gasification performance, since gaseous yields and concentrations are dependent upon the kind of materials, the operating temperature, and the inner pressure, they were examined using the gasifier apparatus which has a reformer and a pyrolyzer. The species of waste wood materials used were Japanese cedar. Through the tests, the syngas components and the equilibrium constants were obtained. For instance, at 550 °C in the pyrolyzer and at 950°C in the reformer, and at S/C=1.0, the following reaction formula would be obtained for 1 kg of material at 20% moisture content.



Also, since we acquire the equilibrium constants on steam reforming reactions, we can estimate the gas components at any reforming temperature in the range of 850°C to 950°C. The H₂/CO ratio of syngas would be approximately 2.7. However, if we prefer the indirect method in the liquefaction plant, the ratio of 2.0 is most suitable as a feed syngas. Thus, in this paper, it is assumed that Char, which is usually consumed for a heat supply, is completely burning in the reformer for the purpose of acquiring the maximum potential of the liquefied fuel. In

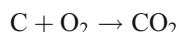
Table 3 Performance of the gasification-liquefaction plant through BLUE Tower process (Operation Conditions: 240°C and 4.0 MPaA)

Process	Items	Products	
		DME	MeOH
Gasification	Scale	10t-dry/d	10t-dry/d
	Fuel Biomass	520.8kg/h	520.8kg/h
		7,108MJ/h	7,108MJ/h
	Auxiliary Biomass	338.5kg/h	307.6kg/h
		4,620MJ/h	4,198MJ/h
	Off-Gas	581.7Nm ³ /h	533.9Nm ³ /h
		1,200MJ/h	1,806MJ/h
	Syngas		
	(Dry-basis)	1,084Nm ³ /h	1,084Nm ³ /h
		8,105MJ/h	8,105MJ/h
Liquefaction	Cold-Gas Efficiency	62.7LHV-%	61.8LHV-%
	Auxiliary Power*	442.0kW	442.1kW
	Product Scale	207.4kg/h	263.3kg/h
		5,975MJ/h	5,186MJ/h
	Operating Pressure	4.0 MPaA	4.0 MPaA
	Operating Temperature	240°C	240°C
	Refining Efficiency	86.1LHV-%	78.6LHV-%

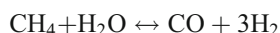
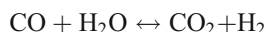
*The auxiliary power of DME/MeOH liquefaction is included in this category

the gasification simulation, the char gasification reaction, due to partial oxidation, is the slowest one in the reactor. However, in the pyrolyzer and reformer, the residual time of char is enough and the inner temperature would be $>1000^{\circ}\text{C}$ through a char combustion. Thus, this assumption would be reasonable to some extent (Dowaki et al. 2007b).

That is, the reaction of:

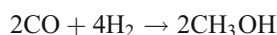


would occur in the reactors, and through the following two reactions (steam reforming) of:



The gas components for a liquefaction process would be adjusted. Using this assumption, the chemical formula as a liquefaction material gas was obtained as Table 2.

- (b) *Production rate of Bio-DME/MeOH through a liquefaction process* Next, we analyzed the liquefied fuel rate, adjusting the compressed pressure. In this paper, the indirect method, which is indicated by the following two reactions, is most suitable.



Obviously from these reactions, DME through MeOH synthesis would be produced in the indirect method. In the recent synthesis method, dehydration of MeOH (i.e. DME synthesis) would occur in the reactor. The reaction would be more advantageous than that of only MeOH synthesis, since there is no influence of MeOH synthesis (NEDO 1999). Thus, we can deal with the production efficiencies of the two syntheses based on the equilibrium theory,

separately. Although the catalysts for synthesis and dehydration are required, these materials are not considered in our estimation.

The operational conditions in the liquefaction plant of DME/MeOH are determined by referring to actual performance of similar plants, the aspects of the catalyst development, and related issues. Here, it is assumed that the reaction temperature and pressure in the liquefaction plant are $210\text{--}290^{\circ}\text{C}$ and $2.0\text{--}5.0$ MPaA of DME/MeOH synthesis, respectively (NEDO 1999; Hamelinck et al. 2001; Moradi et al. 2007). Usually, the pressure of MeOH synthesis is approximately 5 to 15 MPaA, from the viewpoints of economical benefit. However, the operational condition of a higher pressure in MeOH synthesis is not always cost advantageous. Also, the auxiliary power, due to a high compression, would be increased. As the result, the entire CO_2 emissions and/or energy intensities might be worse. The effects on the worse operational conditions, in which the temperature and/or the pressure would be increased, are described below.

- (c) *Process design of the entire system* The capability of the biomass gasification plant is 10 t-dry/day, that is, the annual throughput is approximately 3,000 t/yr. Using these conditions and the experimental data on the gasification, we executed the process designs (Mayer et al. 2004; Dowaki et al. 2007; Dowaki et al. 2007b). For instance, the performance data of DME product in the case of 240°C and 4.0 MPaA, and that of MeOH in the same case are shown in Table 3.

In Table 3, cold gas efficiency (η_{Cold}) is defined as follows:

$$\eta_{\text{Cold}} = \frac{\text{Syngas through a gasifier [MJ/h]}}{\text{Fuel Biomass [MJ/h]} + \text{Auxiliary Biomass [MJ/h]} + \text{Off Gas [MJ/h]}} \quad (7)$$

Also, the refining efficiency means the conversion efficiency of $\text{H}_2 + \text{CO}$ in syngas through a gasifier. Due to

Fig. 2 CO_2 emissions through DME/MeOH production system at 240°C and 4.0 MPaA

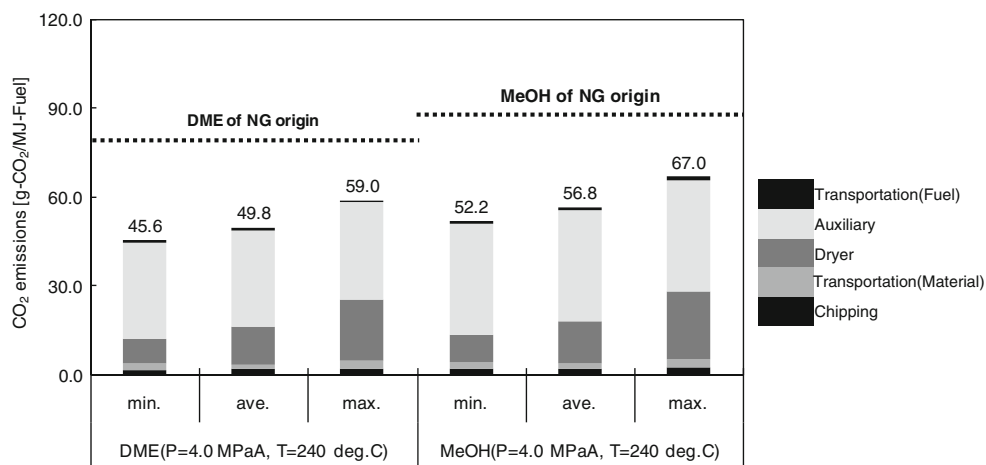
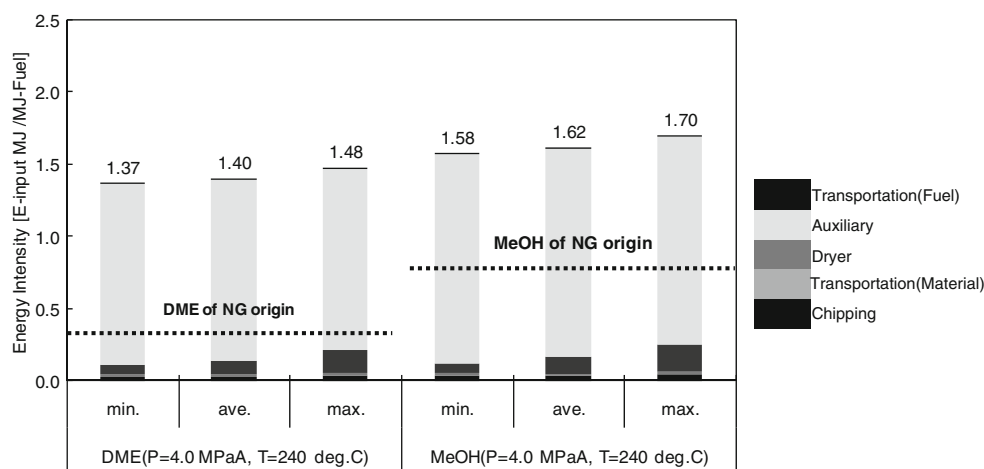


Fig. 3 Energy intensities through DME/MeOH production system at 240°C and 4.0 MPaA



the BT process with a liquefaction process, 0.303 kg-DME/kg-material and 0.420 kg-MeOH/kg-material can be produced. Note that the biomass material for auxiliary heat energy is included in 1 kg-material.

3.3 Sub-processes of delivery of the liquefied fuels

According to the previous study, assuming that the distance between the fuel production plant and the gas station in the domestic area is approximately 209 km round trip, and that tank trucks are used, CO₂ emissions and/or energy intensities were estimated (TOYOTA 2004). Here, the tank capacity of the truck is assumed to be 10,000 L, that is, the fuel consumption rate is the same as that of a 10t-truck. The liquid densities of DME and MeOH are 0.667 kg/L and 0.796 kg/L at 15°C, respectively. Using these data, the loading rate in Eq. (2) was calculated, and CO₂ emissions and/or energy intensities would be estimated.

4 CO₂ emissions and energy intensities on Bio-DME/Bio-MeOH fuels

Based on Table 3 and the data on fuels delivery, CO₂ emissions and energy intensities of Bio-DME and Bio-MeOH fuels at the liquefied temperature of 240°C and the pressure of 4.0 MPaA were estimated in Figs. 2 and 3.

According to Figs. 2 and 3, the entire CO₂ emissions are 45.6–59.0 g-CO₂/MJ-Fuel of Bio-DME and 52.2–67.0 g-CO₂/MJ-Fuel of Bio-MeOH, respectively. Also, energy intensities are 1.37–1.48 MJ/MJ-Fuel of Bio-DME and 1.58–1.70 MJ/MJ-Fuel of Bio-MeOH, respectively. CO₂ emissions at the material drying and at the auxiliary power of a liquefaction process occupy a large portion of the entire CO₂ emissions. Especially, the influence due to the compression power of MeOH/DME synthesis would be significant. In the case of Bio-DME fuel, the amount of

17.9% to 35.2% of the total CO₂ emissions would be emitted from the materials dryer origin, and that of 55.6% to 71.9% would be caused from the auxiliary power origin. In the case of Bio-MeOH fuel, that of 17.4% to 34.4% and that of 56.3% to 72.4% would be emitted from the materials dryer origin and the auxiliary power origin, respectively.

The deviations of CO₂ emissions (the maximum value—the minimum one) due to the uncertainties on the moisture content and the transportation distance would be within 13.4 g-CO₂/MJ-Fuel of Bio-DME and 14.8 g-CO₂/MJ-Fuel of Bio-MeOH. Also, those of energy intensities would be within 0.11 MJ/MJ-Fuel of Bio-DME and 0.12 MJ/MJ-Fuel of Bio-MeOH. Thus, there is a potential to reduce CO₂ emissions due to the alternation of Bio-DME/MeOH fuel from diesel. Compared to the specific CO₂ emissions of diesel, the CO₂ abatement rate would be 2.5–4.1% of Bio-DME and 2.2–3.6% of Bio-MeOH, respectively.

Next, the effects on the operation conditions of temperature and pressure were as follows: In general, in the liquefaction synthesis, a good result (the liquefied fuel at a higher efficiency) is obtained as the pressure would be increased. Also, the temperature to encourage the reaction

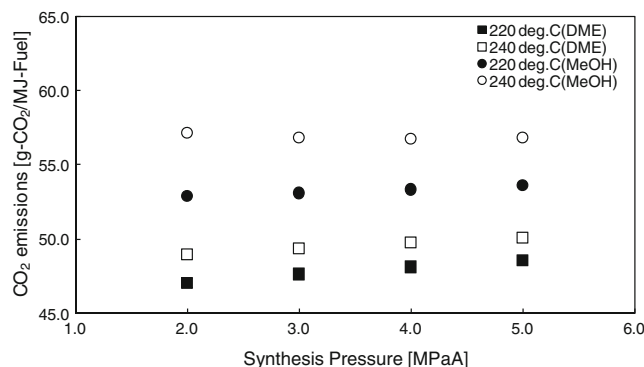


Fig. 4 Environmental influences on the temperature and the pressure through DME/MeOH production system

well is required to some extent. Figure 4 indicates the influences on the temperature and the pressure.

In this figure, the variations of CO₂ emissions are shown at the time when the operational conditions are the liquefied temperature of 220 and 240°C, and the pressure of 2.0–5.0 MPaA. According to Fig. 4, the specific CO₂ emissions would decrease as the temperature drops. Note that the minimum temperature of DME or MeOH synthesis is at least 210–220°C. Meanwhile, CO₂ emissions would be worse as the pressure increases. However, in the case of Bio-MeOH fuel, there is a case that CO₂ emissions would be slightly improved. This implies that the production rate is depending upon the pressure rather than the temperature.

In all conditions we analyzed, Bio-DME/MeOH production indicated that energy intensities were lower than 2.0 MJ/MJ-Fuel, and that there was a potential to mitigate CO₂ emissions.

5 Conclusions

Based on the above analysis results, the following knowledge was obtained.

- 1) Using the BT plant with a liquefaction process, we estimated CO₂ emissions and energy intensities on Bio-DME and Bio-MeOH fuels. CO₂ emissions were 42.4–64.6 g-CO₂/MJ-Fuel of Bio-DME and 48.3–77.7 g-CO₂/MJ-Fuel of Bio-MeOH, respectively. On the other hand, energy intensities were 1.22–1.65 MJ/MJ-Fuel of Bio-DME, and 1.42–2.03 MJ/MJ-Fuel of Bio-MeOH, respectively.
- 2) Especially, on the performance of gasification, the process design was executed by the data based on the chemical experiments. For instance, we evaluated the production rate of 0.303 kg-DME/ kg-material and 0.420 kg-MeOH /kg-material at 240°C and 4.0 MPaA.
- 3) Also, according to the Monte Carlo simulation on the moisture content and the transportation distance, the deviation of CO₂ emissions would be within 13.4 g-CO₂/MJ-Fuel of Bio-DME and 14.8 g-CO₂/MJ-Fuel of Bio-MeOH.
- 4) Considering the fuel alternation from Bio-DME or Bio-MeOH to diesel, the CO₂ abatement rate would be 2.5–4.1% of Bio-DME and 2.2–3.6% of Bio-MeOH, respectively.
- 5) CO₂ emissions and/or energy intensities are affected by the operational conditions of the pressure. Thus, due to the demo-plant of the BT process with a liquefaction process, the performance tests would be required.
- 6) Finally, it is necessary to ensure the marketability of the liquefied fuels in the near future.

6 Recommendations and perspectives

The LCA of the small scale biomass energy system we treated in our study is extremely significant to build a sustainable biomass energy system, since we presume that the utilization of biomass resources would compete with other strategies such as food production, etc. For future work, the feasibility studies on the wheel efficiency and/or the investigation of demand of DME/MeOH will be required from the perspectives of a diversity of energy sources, and/or alternative fuels use.

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